Fermilab

TM-1016
1100.300

Shielding Calculations for the B-O Colliding Detector Area

J. D. Cossairt

June 7, 1982

Crucial parts of the proton-antiproton collision scheme are the colliding detector areas to be constructed in the B-O and D-O straight sections. At the present time this B-O area is ready for construction while preliminary efforts on D-O are being made. This report is a part of that design effort and represents shielding calculations for the B-O area as it is shown in the Title I report.

1. General Comments

Some general comments regarding the biological shield for this area need to be made at the outset. Fig. 1 is a general plan view of the B-O colliding beam area while Fig. 2 is an elevation view of the same area. The detectors (forward angle, backward angle, and central detector) may be either installed in the beam line ("detector in" position) or be in the assembly hall ("detector out" position). In either case the assembly hall can be assumed to have high occupancy by visiting experimenters, contractor personnel, and Laboratory personnel during both fixed target and colliding beam operations. The area on top of the berm will have minimal occupancy and is subject to less stringent requirements. The collision hall will, in both operational modes, be an exclusion area.

At the time of the present work the beam intensity for Tevation operations is not well defined. For the calculations described here, 10^{14} 1000 GeV protons per pulse was assumed. During collider operation 10^{12} particles in each of the two beams is a more realistic intensity. It is clear that in both modes of operation only accidental beam losses will contribute to radiation exposure in either the assembly hall or on top of the berm since in either physics program (fixed target or colliding beam) the B-0 region will be free of planned targeting (neglecting the p-$\bar{p}$ collisions!) An important implication of this is the absence of any problems involving soil activation and, for the most part, radioactivation of components. The restriction of beam losses to accidental losses at this location clearly serves to reduce the quantity of shielding required.

2. Lateral Shielding Calculations

The Monte Carlo Code CASIM[1] was used to calculate the dose equivalent expected for 10^{14} 1000 GeV protons (or antiprotons) targeted in several ways. It is clear that the loss of 10^{14} circulating hadrons in a localized region of a superconducting accelerator is a highly improbable catastrophic event. It is improbable for a circulating beam because of constraints of magnet time constants coupled with the initial condition of a circulating beam along with aperture limitations. It is more probable for an injected beam not yet circulating but such a beam would be limited to the Doubler injection energy. It is catastrophic because of the possible severe damage done to accelerator components. Such a catastrophic beam loss would likely be self limiting in that it would serve to shut down the accelerator. Radiation detectors should certainly be used to effect a shut down in the event of such losses. Thus, in the remainder of this work only one such accident pulse need be considered. These different cases are described in Table 1 and are meant to describe several possibilities with different beam elements installed in the B-0 straight section. Cases 1 through 5 are for various configurations involving the "detector out" situation and for each of these cases, several different locations within the collision hall for the simulated beam loss were chosen. The shielding geometry is that provided by the 12 ft. thick movable shielding wall since that wall protects the area with the highest occupancy. This was done to test the dependence of external dose rate upon the location of the loss point, since the locations or size of beam line components in the hall were unknown at the time of this report. Case 6 is the "detector in" case. Dose rates on top of the berm and elsewhere may be obtained by using the usual "3 ft./factor of 10 rule" for cases involving small changes in shield thickness and radial dimensions. The calculations were carried out for a shield 14 ft. thick to provide the reader a calibration for small changes in shield thickness.

Figures 3-19 display contours of dose equivalent/10^{14} protons in units of mrem as a function depth (z) (downstream along the beam line axis) and radius for Cases 1-6. An "x" on the Z axis denotes the loss point of the beam. These contours were derived from the star densities (stars/cm^3·proton) calculated by the Monte Carlo program using the conversion factor 10^{-5} rem/star·cm^3 which is valid for areas external to concrete shields greater than about 100 cm in thickness. If the concrete shielding is replaced with iron shielding to obtain a reduction in the space required then the precautions discussed by Gollon in TM-664 must be observed.[2] The placement of the concrete shield in

Figs. 3-18 is slightly different than that of Fig. 19. While that of Fig. 19 is the one most nearly like the configuration to be used, the differences are of little consequences as long as one compares doses at equal shielding thicknesses.

From Figs. 3-19 it is clear that the worst cases encountered are those involving the "detector out" configuration. As one would expect from intuitive reasoning, a loss on the central detector produces lower radiation levels because the detector itself is a massive object that it is significantly self-shielding. However, it is difficult at the present time to determine locations of beam line components (e.g., low β quadrupoles) which would be associated with the central detector and contribute loss points less well shielded. No calculations were done specifically for the forward or backward detectors but the "detector out" cases should cover these conservatively. As one can see from these results, the worst dose equivalent rate seen in these calculations is 50 mrem/10^{14} with 12 ft. of concrete shielding. The doses expected on top of the berm as a function of Z over the roof will be virtually identical to the ones calculated here.

3. Muons

Because it is presently planned to locate the B-O Colliding Detector area so that the assembly hall is external to the Main Ring, accidental beam losses in the Main Ring or Energy Doubler upstream of the Colliding Detector Area could contribute radiation exposure from muons to persons working in the assembly hall. Because of the depth below grade of the plane of the accelerator, there should be no muon exposure outside of the assembly hall. In this section an estimate is made of the muon hazard. It should be stated that no muon radiation exposure problem would exist if the assembly hall were inside of the Main Ring. This consideration should be remembered in the design of future collision halls of this type.

Muon dose rates have been calculated using Monte Carlo techniques by Van Ginneken.[3] In the case of muon dose rates, the problem is restricted to forward angles and the worst doses are found at zero degrees. The worst exposure would be expected in the plane of the Energy Doubler in the assembly hall next to the shielding door. This point is 37 feet from the beam center line in the collision hall. Such a point is on a line tangent to the Energy Doubler 151 meters upstream of an estimate of the location at which an estimate of the muon flux is desired. Using the results of Ref. 3 (including both prompt and decay muons) for 1000 GeV incident protons one obtains 2×10^{-8} muons/cm$^2\cdot$proton. This implies a dose equivalent of 71 mrem/10^{14} protons. At 65 feet radially from the center line the location of interest is on a line tangent to the Energy Doubler 209 meters upstream, the dose is reduced to 35 mrem/10^{14} protons.

If the loss point were 100 meters upstream of the Colliding Detector area the muon flux at the outside of the shielding wall would be 2×10^{-11} muons/cm$^2\cdot$proton so that one can see the rapid decrease in dose equivalent rate as one leaves the axis defined by the tangent to the Energy Doubler at the loss point. The half angle of the muon cone for half maximum is, at these distances of soil shield from the loss point of around 150-200 meters, approximately 3 milliradians.

The above was done for a loss of beam at a point. Any loss of beam over a lengthy region of the Energy Saver would reduce the dose equivalent accordingly and sweep out a band of exposed region in the assembly hall. For example, if the above loss 200 meters upstream were a uniform loss over 60 meters (three 22 ft. dipoles) instead of a point loss, the hot spot (down to half maximum) would be spread over a 3 meter by 1.2 meter area instead of the circle of 0.6 meter radius circle (down to half maximum) obtained with the point loss. One would thus expect a dose of 11 mrem/10^{14} protons (applying the ratio of the areas to the 35 mrem). Beam losses over more extensive regions would thus further reduce the muon dose equivalent rates.

4. Labyrinth Shield Door

A special concern is the 8 ft. thick shielding door which blocks the side labyrinth shown in Fig. 1. The labyrinth itself is a rather standard one and from Fermilab experience is quite adequate. Following Gollon and Awschalom,[4] the 1st leg is 6.1 "units" long where a unit is $\sqrt{A}$ (A is the cross sectional area). A labyrinth this long attenuates the neutron flux by a factor of 0.02. From the mouth (tunnel side) of the labyrinth to the loss point it is 18' so that using the fact that 1 neutron/GeV is emitted isotropically and 3×10^7 n/cm^2 is approximately 1 rem of dose equivalent at the mouth of such a labyrinth we have at 1000 GeV:

$$\frac{1000\ n \times 10^{14}\ \text{protons}\ \text{rem}}{4\,\pi\, r^2\ \text{proton}\ \ 3 \times 10^7\ n/\text{cm}^2} \cong 881\ \text{rem}$$

Putting in the attenuation of the shield door ($10^{-8/3}$) and the labyrinth, we have:

$$\frac{881 \text{ rem}}{10^{14} \text{ protons}} \times 0.02 \times 10^{-\frac{8}{3})} = 38 \frac{\text{mrem}}{10^{14} \text{ protons}}$$

external to the shield. This dose equivalent is very comparable to that found outside the large 12 ft. thick door under catastrophic accident conditions. The two doors are sufficiently separated in distance for the maximum doses not to be cumulative at the same location.

5. Estimate of Dose Rates in the Computer Area Counting Room

The dose equivalent rates under all operating conditions in the three story counting room (See Fig. 1) are of prime concern because of the high occupancy of these areas. If one determines the amount of shielding present on a line between each level and the center line of the nearest beam (either Main Ring or Doubler) and scales the above CASIM results according to the usual rule of a factor of 10 per 3 feet of laterial shielding, one obtains the following (in vertically ascending order) for the loss of 10^{14} 1000 GeV protons:

level 1 (14.2 ft. shield) - 9 mrem

level 2 (16.5 ft. shield) - 2 mrem

level 3 (16.5 ft. shield) - 2 mrem

Level three is shielded by no more than level two because it is high enough that it now looks down through the thin berm covering the roof of the hall.

Under the present Laboratory policy (see Appendix I) an area having 9 mrem/interlock trip requires posting it as a radiation area having "minimal occupancy." However, the liklihood of such a one pulse catastrophic disaster occurring more than once during any reasonable period of time is extremely, if not vanishingly, small. Certainly, no serious hazard to personnel is predicted for this area. Muons are not a problem here because these areas are above the plane of the Main Ring.

6. Analysis of Shielding of the Proposed Main Ring Overpass

The presently proposed design provides for at least 17' of soil shielding over these tunnels everywhere except at B-O itself. Rather than do an original calculation it is sufficient here to scale from radiation measurements previously published.[5] In Ref 5, case C there a situation involving a collimator in a tunnel shielded by approximately 15 ft. of soil (451 cm). In this case a dose of 20 μrem (quality factor = 5) per 10^{11} protons dumped on the collimator at 350 GeV was measured. This scales to 5 mrem per 2.5 x 10^{13}. With 2 more feet of soil shielding this becomes about 1.2 mrem/2.5 x 10^{13} protons. Since more than 10 such pulses during a one run period is virtually impossible, in these areas, compliance with the Radiation Guide (see Appendix I) is thus obtained. An additional safety factor is provided by the fact that the Main Ring in this configuration would be limited to 200 GeV.

In general, the Energy Doubler is shielded by at least six more feet of soil and shadowed by the Main Ring magnets so that the loss of 10^{14} 1000 GeV protons would cause even lower doses. Such a total dump of the beam is highly unlikely to occur more than once. Near the ends, however, the two accelerators are in the same tunnel. There the drawings (Fig. 20) show 18 ft. in all places so that the Main Ring dose atop such a loss point becomes about 0.3 mrem/2.5 x 10^{13} at 200 GeV while the doubler loss produces approximately 6 mrem/10^{14} protons at 1000 GeV (scaling linearly with energy, which is conservative. The road crossing at A46-47 (shown in Fig. 20) is a potential problem. However, with 4' of steel shielding installed under 3' of granular fill, we arrive at an equivalent of 16' of soil which may be barely adequate, for such a longitudinally small region, since the dose here scales to 1.4 mrem/2.5 x 10^{13} 200 GeV protons. The same comment holds for the building at A-45 shown in Fig. 21.

At the B-O collision region (see Fig. 22) we have a much thinner shield (11 feet) but only a situation of scraping on a pipe with the 200 GeV Main Ring beam. Scaling from the above, one obtains a dose of about 100 mrem per 2.5 x 10^{13} in a fenced area protected by the same interlocked radiation detectors which would sense the Doubler "one pulse" accident.

Muons resulting from loss of beam at the point where the Main Ring beam is brought back to horizontal can be estimated as was done above for the assembly hall using the results of Ref 3. Such a loss creates a maximum dose of 9 mrem/2.5 x 10^{13} 200 GeV protons directly over B-O in the fenced area over the thin shielding.

7. Radiation Protection Criteria and Summary

Since the accidental loss of beam in the vicinity of the Colliding Detector area is highly undesirable for a variety of reasons and very likely to be infrequent, during both modes of the physics program it is reasonable that interlocks activated by radiation detectors would be used to turn off the beam in such cases. The present Laboratory standards applying to such areas are listed in section 6.1.3 of the Fermilab Radiation Guide. The pages most relevant to the present discussion are included here as Appendix I. The "access by authorized personnel only" listed for the $10<D<50$ mrem/interlock trip range could include suitably trained contractor, visitor and Laboratory personnel wearing proper dosimetry and working in the assembly hall with appropriate access control. This is the highest dose range where access is presently permitted. For the outdoor radiation on top of the berm these rules apply so that, from Figs. 3-19 and these rules one can estimate the restrictions required to protect the general public with a given thickness of earth berm.

From these results it thus is concluded that the presently designed shielding is adequate for 10^{14} 1000 GeV protons insofar as lateral shielding of both the assembly hall and outdoor area on top of the roof are concerned since the maximum dose equivalent is less than 50 mrem per 10^{14} 1000 GeV protons. The muons present a serious problem, possibly slightly exceeding 50 mrem per 10^{14} protons in a localized region in the assembly hall. It is concluded that the Main Ring overpass is adequately shielded for 1000 GeV beams. For the 200 GeV beam in the Main Ring, the fence around the area above the collision hall would require interlocked gates.

I would like to thank L. Coulson, D. Theriot, J. Couch and J. Peoples for their helpful discussions relating to this work.

References

1. A. Van Ginneken, "CASIM: Program to Simulate Transput of Hadronic Cascades in Bulk Matter," FN-272, January, 1975.

2. P. J. Gollon, "Dosimetry and Shielding Factors Relevant to the Design of Iron Beam Dumps," TM-664, March 17, 1976.

3. A. Van Ginneken, "Penetration of Prompt and Decay Muon Components of Hadronic Cascades through Thick Shields," TM-630, November 25, 1975.

4. P. J. Gollon and M. Awschalom, "Design of Penetrations in Hadron Shields," in CERN 71-16, Vol 2 p 267.

5. J. D. Cossairt, N. V. Mokhov, and C. T. Murphy, "Absorbed Dose Measurements External to Thick Shielding at a High Energy Proton Accelerator: Comparison with Monte-Carlo Calculations," Nucl. Instr. and Meth., to be published.

6.1.3 "Outdoor" Areas (cont.)

Table 2B addresses controls for areas which are protected by radiation activated interlocks. Such areas must be searched and secured before the dose exceeds 250 mrem during any one hour period. For example, if the dose per interlock trip is 100 mrem, then the area must be searched before resetting if two interlock trips occur within one hour.

TABLE 2B CONTROL OF "OUTDOOR" RADIATION AREAS AGAINST "ACCIDENT" RADIATION LEVELS: RADIATION INTERLOCKS USED

Maximum Dose/Interlock Trip	Level of Precaution
D < 0.25 mrem	No precaution needed, no occupancy limit
0.25 $\leq$ D < 2.5 mrem	No precaution needed, minimal occupancy
2.5 $\leq$ D < 10 mrem	Signs and ropes, minimal occupancy
10 $\leq$ D < 50 mrem	Signs and fences with locked gates. Access by authorized personnel only
50 $\leq$ D < 100 mrem	Signs and fences with interlocked gates. No access permitted with beam-on
100 $\leq$ D < 250 mrem	Signs, 8' high fences with interlocked gates and hardware requiring a search and secure. The area must be searched and secured by authorized lab personnel before the beam is turned on and after each interlocked trip. No access permitted with beam-on.

6.1.3 "Outdoor" Areas (cont.)

3. Special Circumstances

A. Guard Coverage - With the prior approval of the Safety Section Head, continuous Site Patrol (guard) coverage may be used as a short-term substitute for fencing and interlocking requirements.

B. Higher Levels - The possibility of higher severity accident conditions could be permitted if the level of precaution taken is much greater i.e., sufficient to make undetected entry extremely unlikely. For all such cases the approval of the Safety Section Head is required. An example of what might be considered satisfactory is given below.

For cases where the maximum dose per interlock trip is greater than 250 mrem but less than 1000 mrem at least the following precautions shall apply: double fences (one being at least 8' high with barbed wire on top), all gates interlocked, flashing lights warning of the hazard, hardware to require a rigorous search and secure after each gate interlock trip, sufficient lighting to ensure a careful search and secure, interlocks redundant and fail safe, daily inspection of the fences during operating periods.

Table 1

Case 1: A 4 inch diameter steel beam pipe with 0.125" thick walls runs throughout the straight section. A 2mm diameter beam scrapes on this pipe at 10 milliradians.

Case 2: A 2mm diameter beam scrapes at the upstream end of an EPB quadrupole at 10 milliradians. The quadrupole is located at various places in the collision hall.

Case 3: A 2mm diameter beam scrapes as in Case 2 on the upstream end of a string of 4 EPB quadrupoles. The string is located at various places.

Case 4: A 2mm diameter beam hits the upstream end of a string of 4 EPB quadrupoles at 10 milliradians. The point of impact is at a radius of 5 cm relative to the beam axis. The quadrupole string is located at various places.

Case 5: A 2mm diameter beam hits upstream end of a string of magnets 1200 cm long with inner dimensions equivalent to an EPB quadrupole but with an outer radius of 50 cm. The point of impact is at a radius of 5 cm relative to the beam axis and the angle of impact is 10 milliradians. The magnet string is located at various places.

Case 6: A 2mm diameter beam hits the upstream end of the Central Detector (with the plug limiting the aperature to 6^{o} in place) at 10 milliradians at 40 cm radius from the beam axis.

Figure Captions

1. Plan view of the Colliding Detector area in the horizontal midplane of the Central Detector.

2. Elevation view of the Colliding Detector area in the vertical midplane of the Central Detector perpendicular to the beam direction (top) and parallel to the beam (bottom).

   Figures 3-19 are contour plots of equal dose equivalent (mrem per 10^{14} protons) as a function of depth (Z) (cm down the beam axis) and radius for the cases described below for losses at various depths. The outline of a plan view of the collision hall is shown in these figures.

3. Case 1, loss point at Z = 0.0 cm
4. Case 1, loss point at Z = 500.0 cm
5. Case 1, loss point at Z = 1000.0 cm
6. Case 1, loss point at Z = 2000.0 cm
7. Case 2, loss point at Z = 1.0 cm
8. Case 2, loss point at Z = 1000.0 cm
9. Case 2, loss point at Z = 2000.0 cm
10. Case 3, loss point at Z = 500.0 cm
11. Case 3, loss point at Z = 1000.0 cm
12. Case 3, loss point at Z = 2000.0 cm
13. Case 4, loss point at Z = 500.0 cm
14. Case 4, loss point at Z = 1000.0 cm
15. Case 4, loss point at Z = 2000.0 cm
16. Case 5, loss point at Z = 500.0 cm
17. Case 5, loss point at Z = 1000.0 cm
18. Case 5, loss point at Z = 2000.0 cm
19. Case 6

20. Main Ring Overpass Design as of 10/6/81 - Road at A-46

21. Main Ring Overpass Design as of 10/6/81 - Building at A-45

22. Main Ring Overpass Design as of 10/6/81 - Cross Section at B-O showing Main Ring Overpass

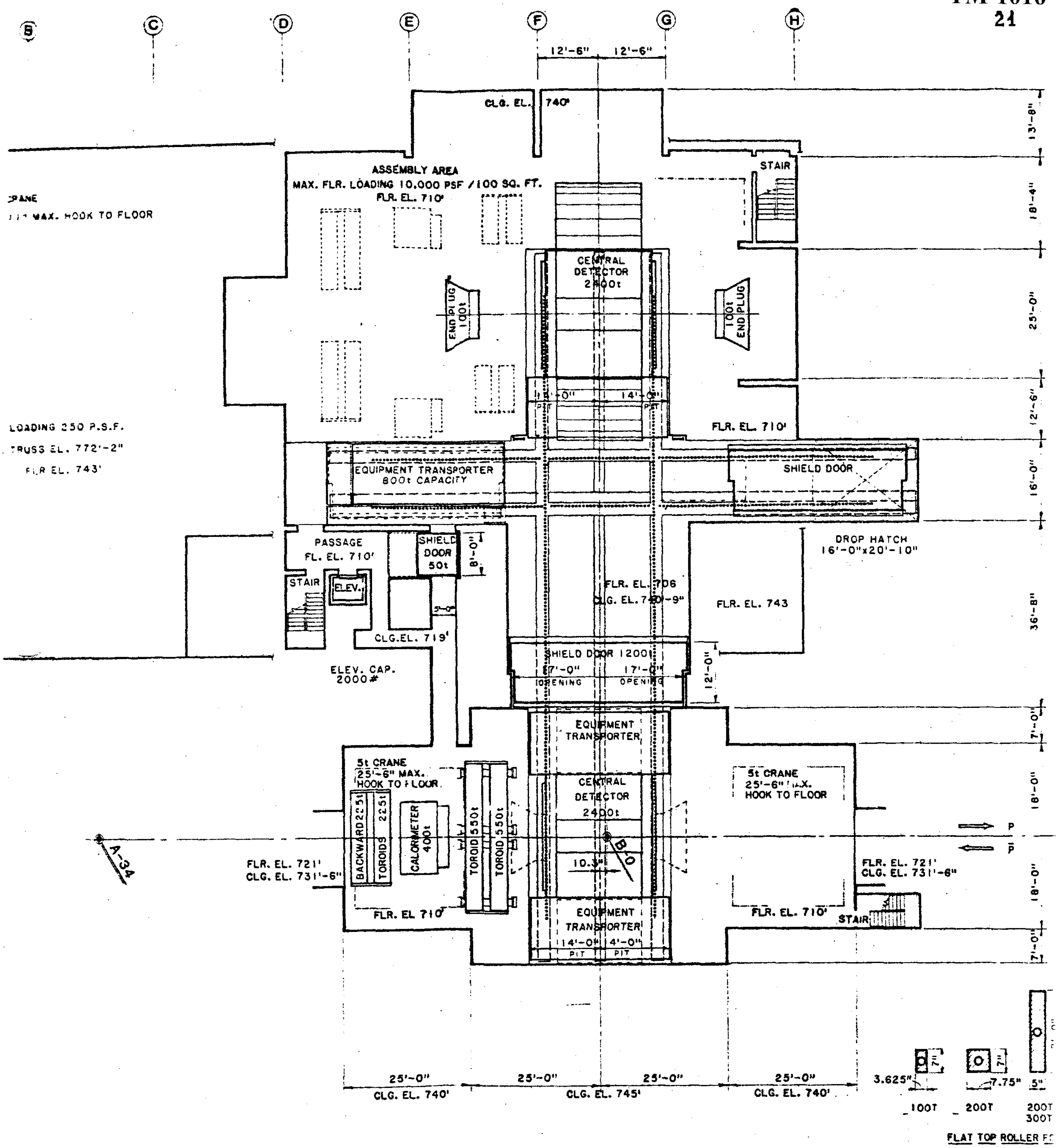
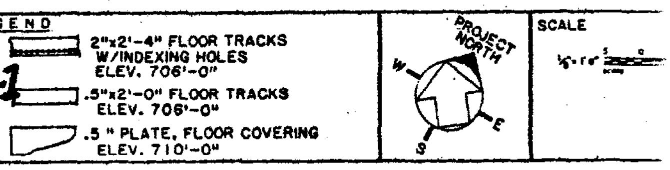
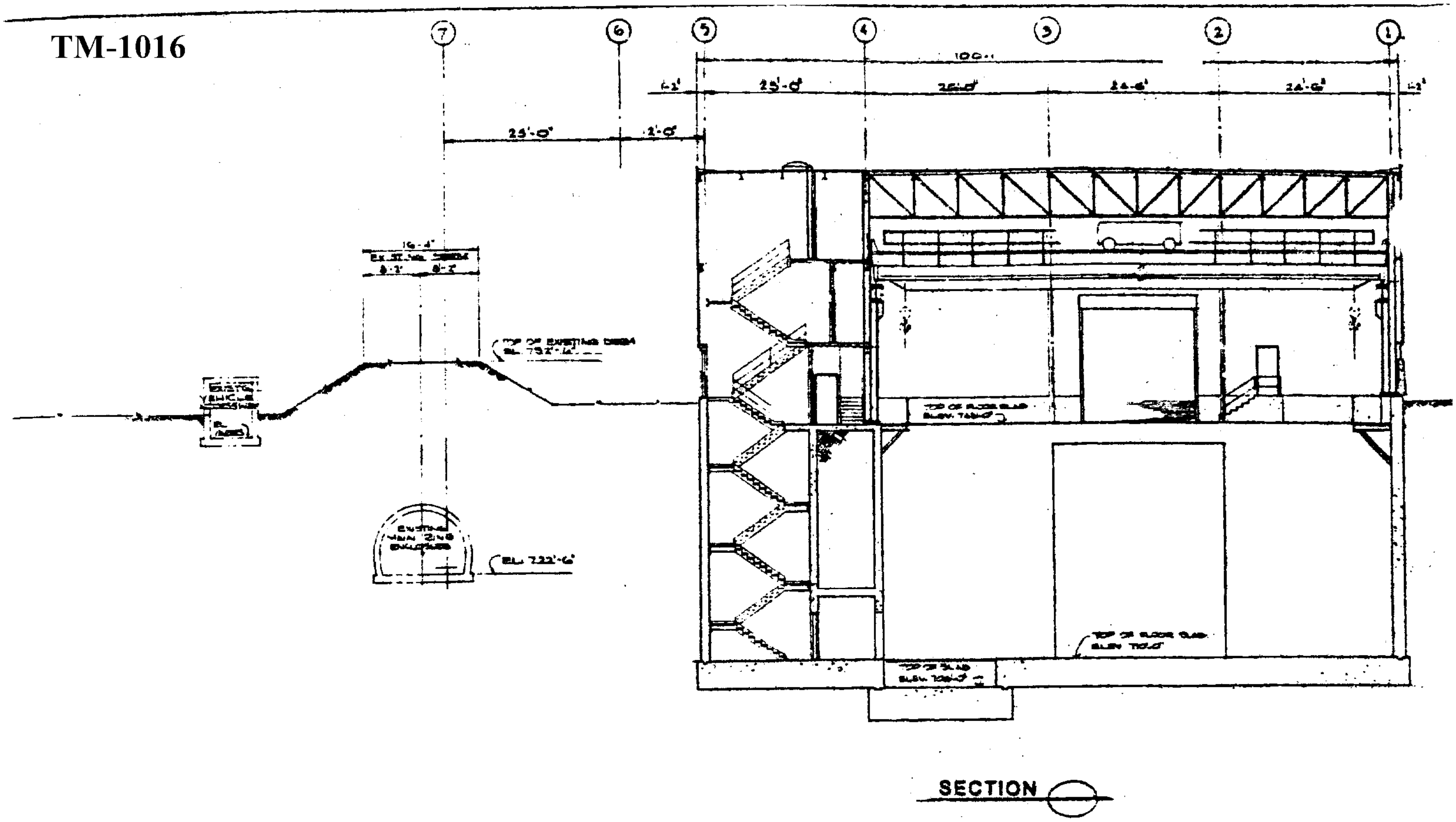


Figure 1 Part of Drawing 6-1-37 Title I Report X-1





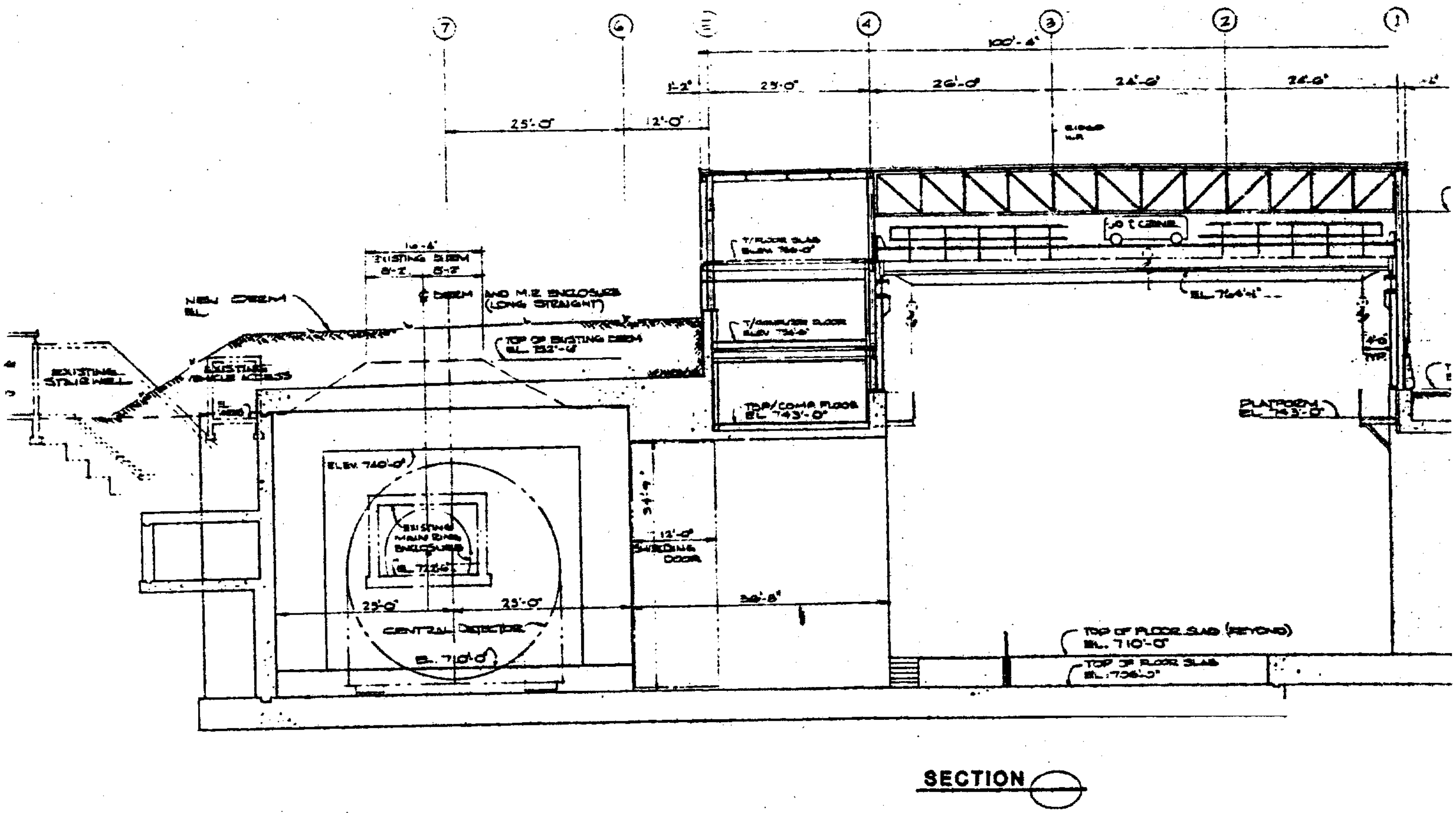


Figure 2 Part of Drawing 6-1-37 Title I Report A6

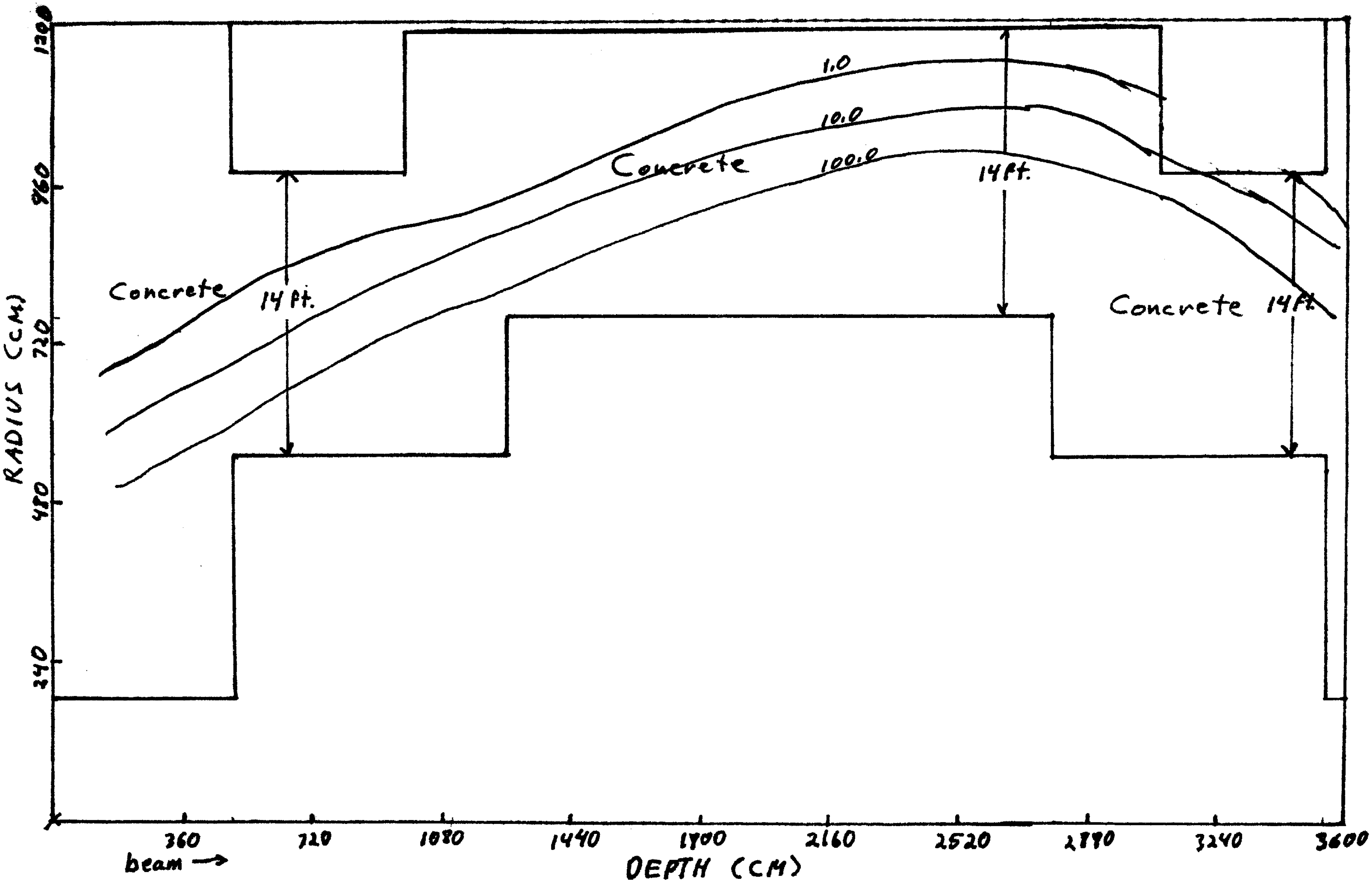


Figure 3 Case 1, Loss Point at z = 0.0 cm

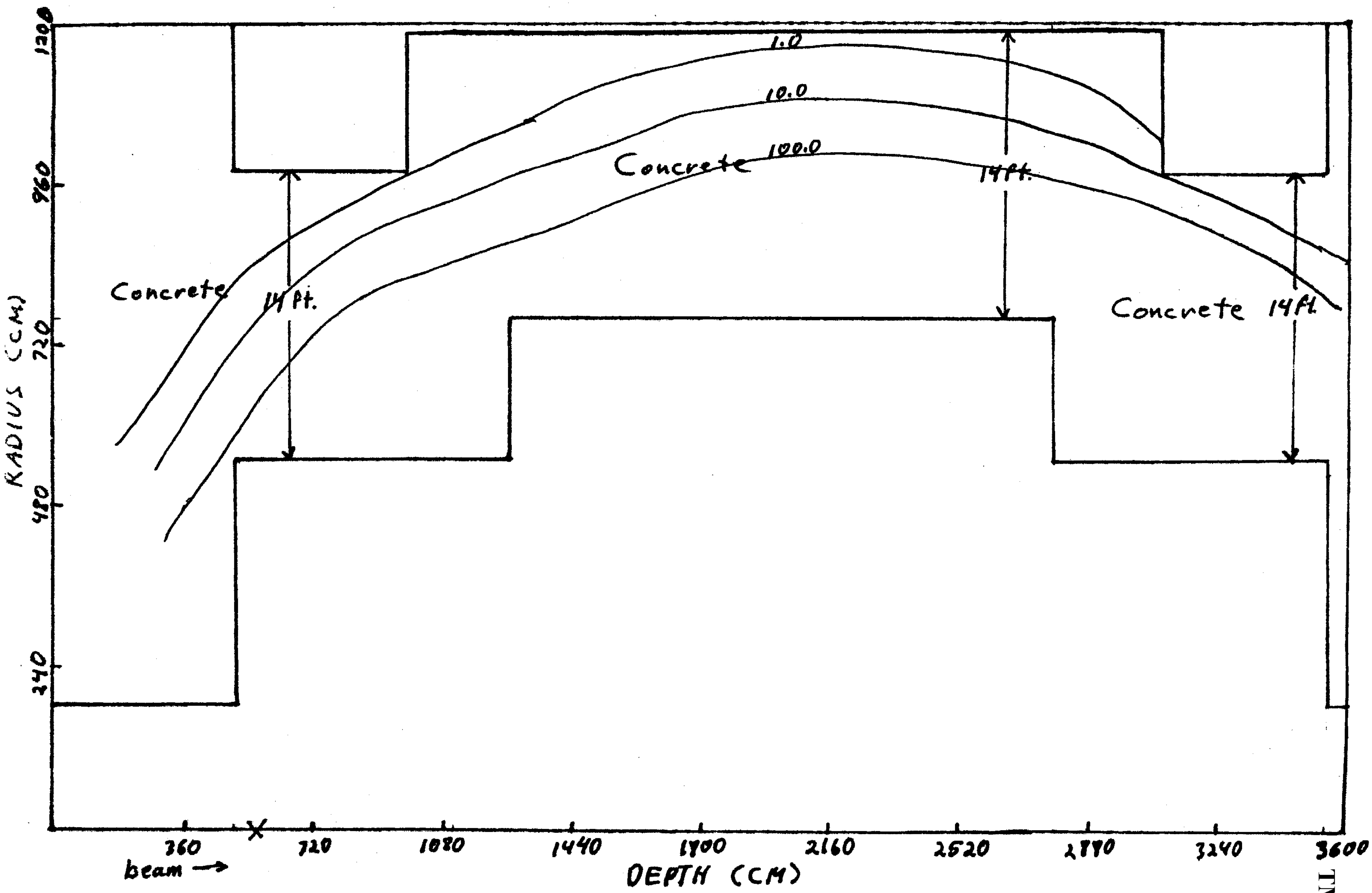


Figure 4 Case 1, Loss Point at z=500 cm.

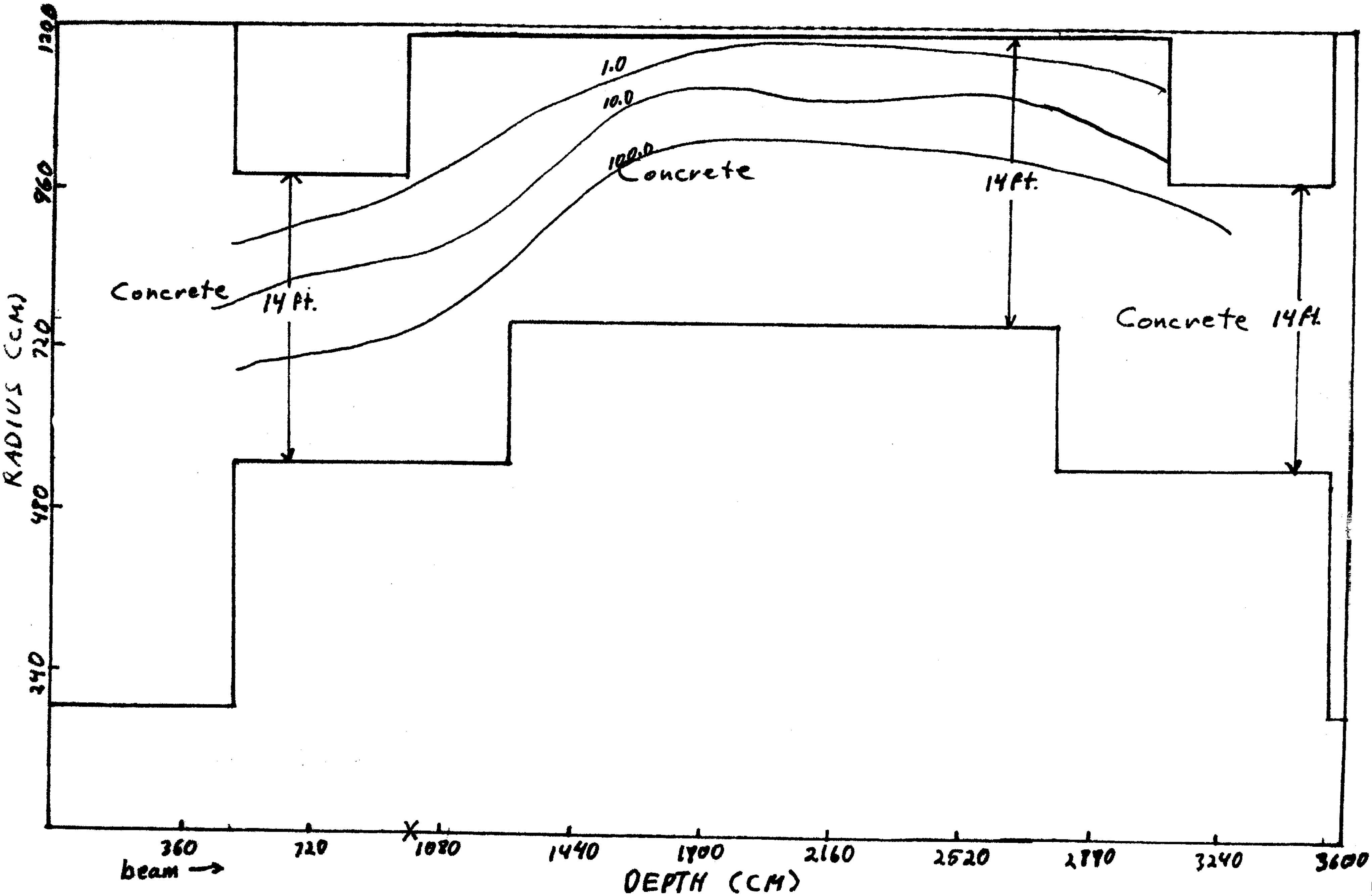


Figure 5 Case: 1, Loss Point at Z = 1000.0 cm.

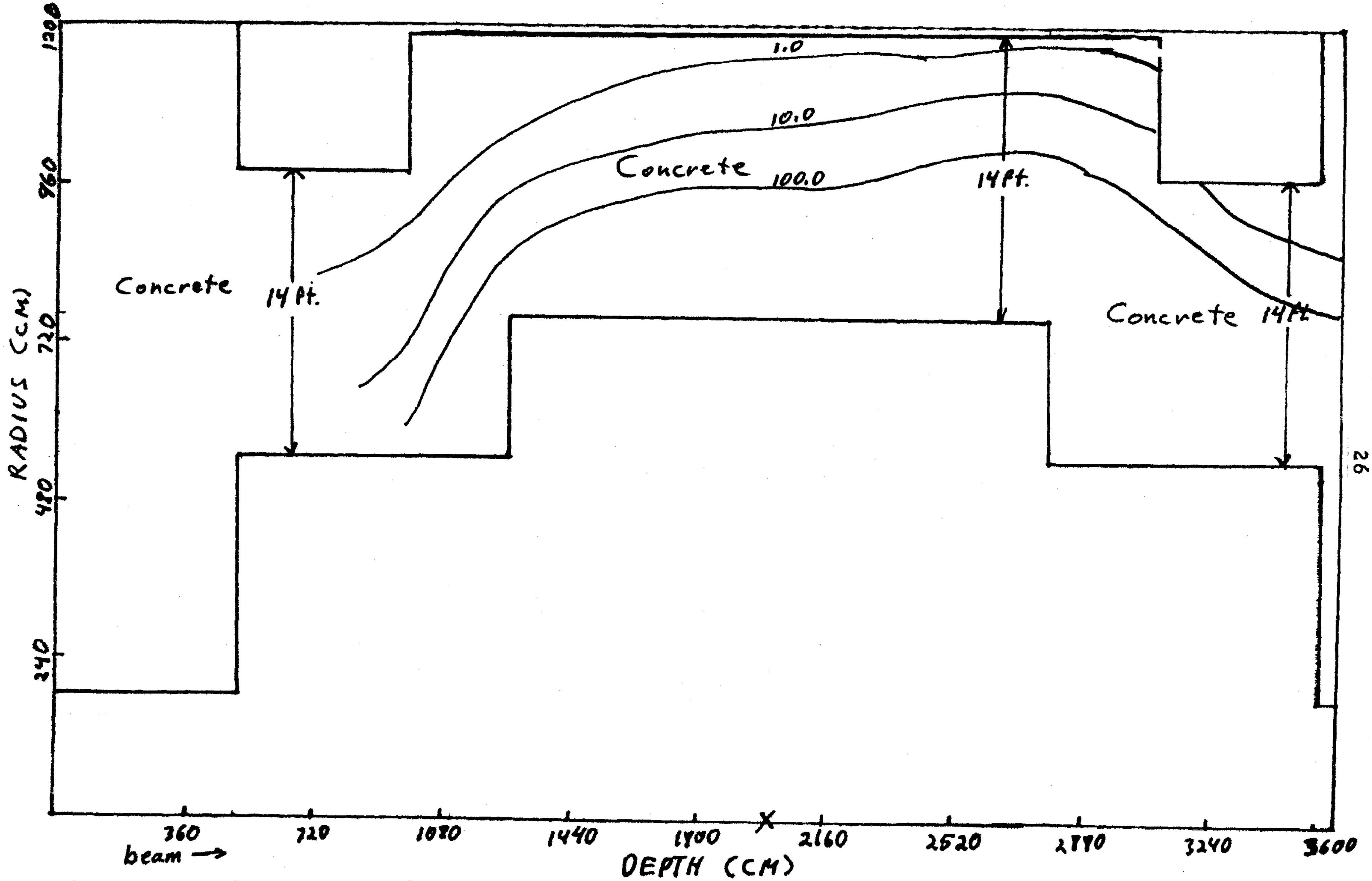


Figure 6 Case 1, Loss Point at z=2000.0 cm.

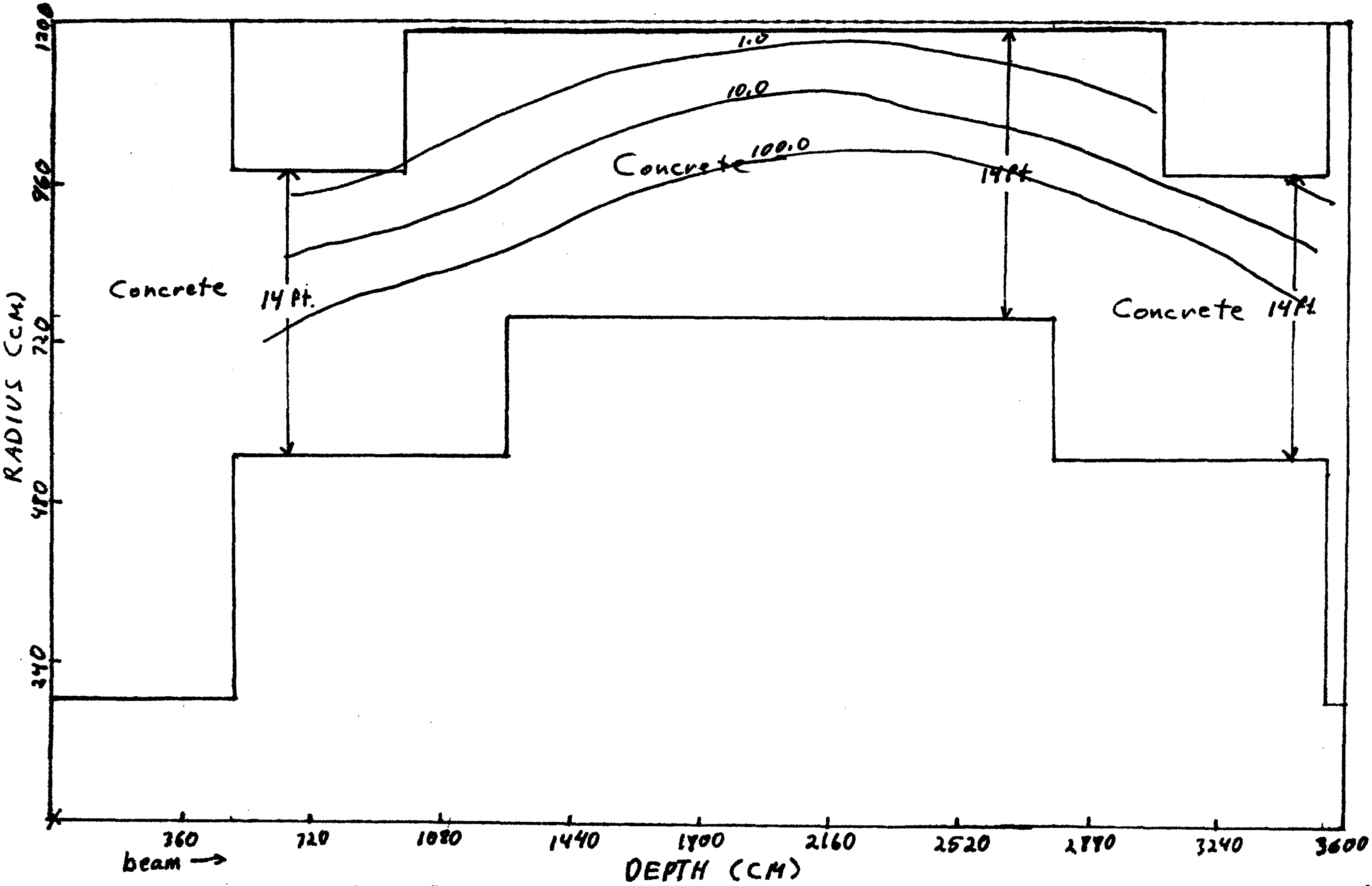


Figure 7 Case 2, Loss Point at $z = 1.0$cm

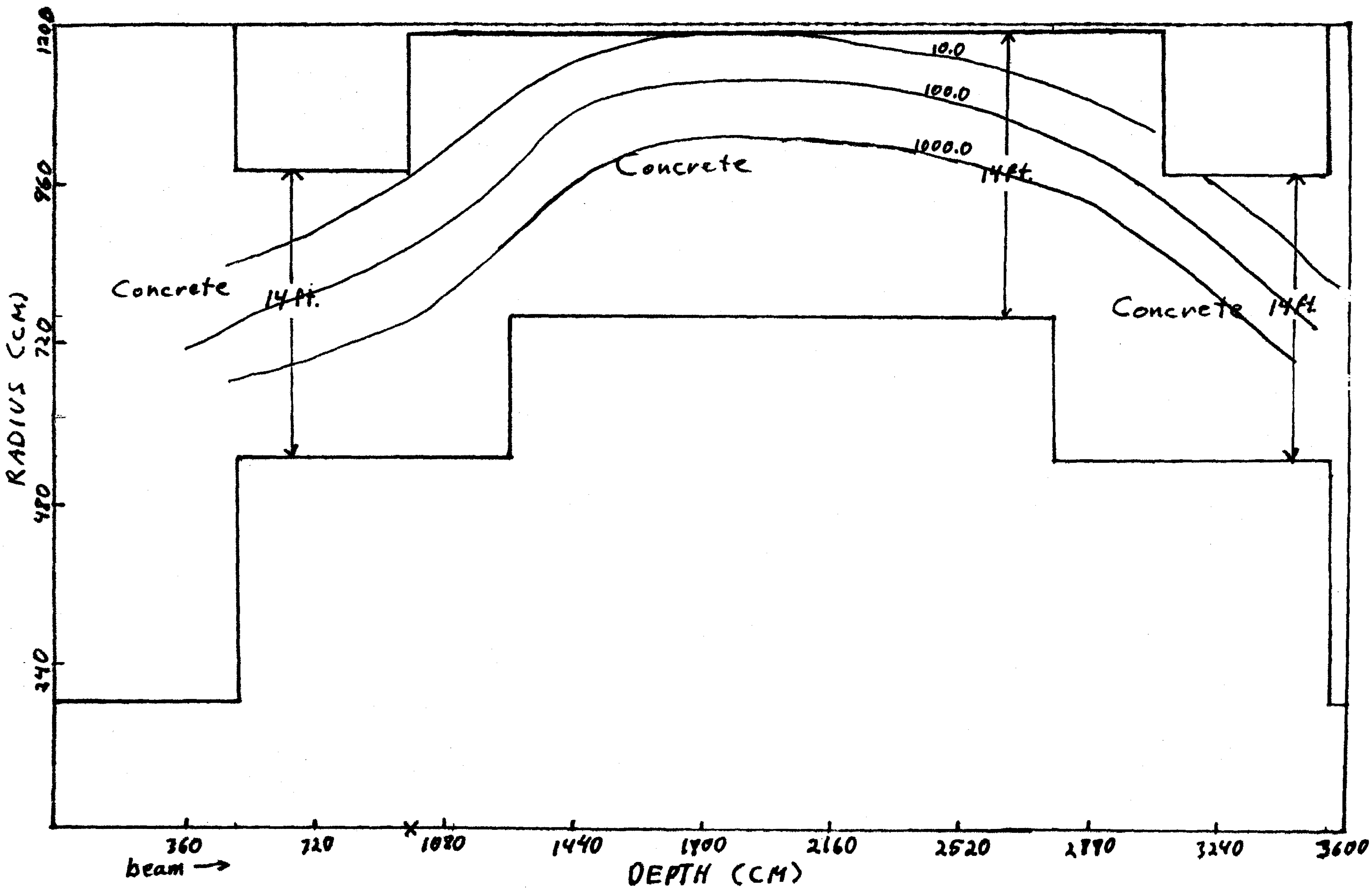


Figure 8 Case 2, Loss Point at z = 1000.0 cm

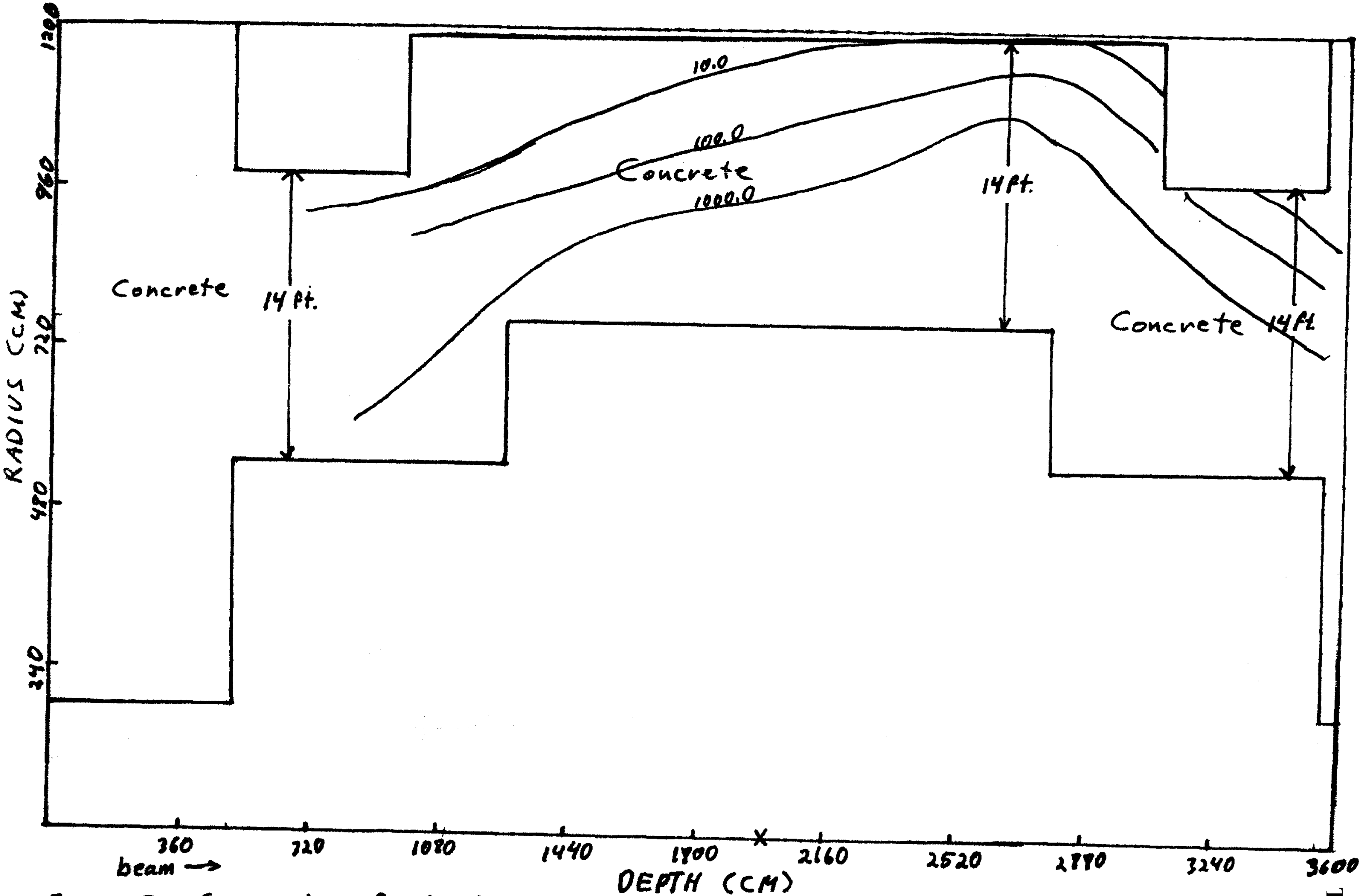


Figure 9 Case 2, Loss Point at z=2000 cm.

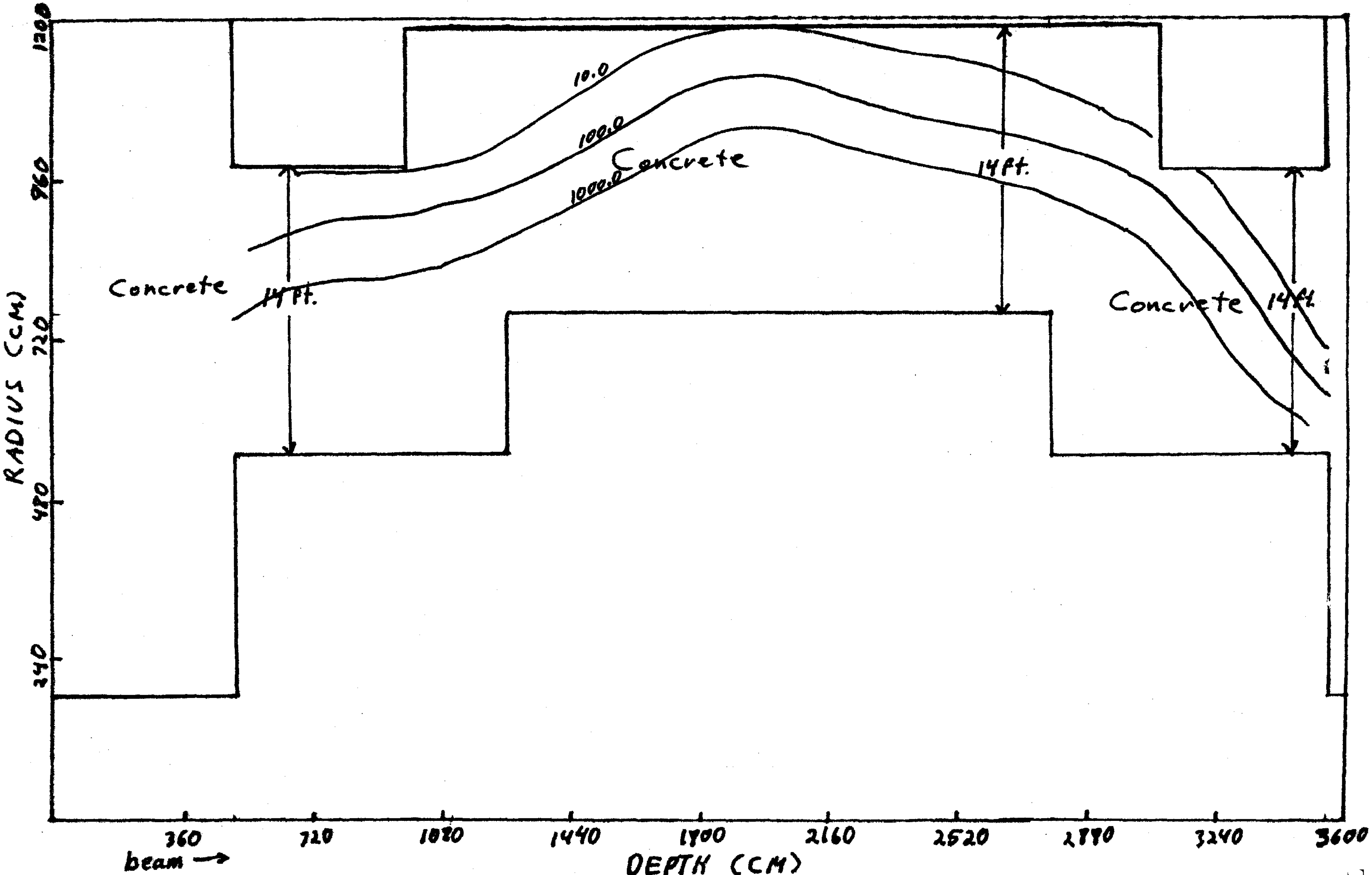


Figure 10 Case 3, Loss Point at Z = 500 cm.

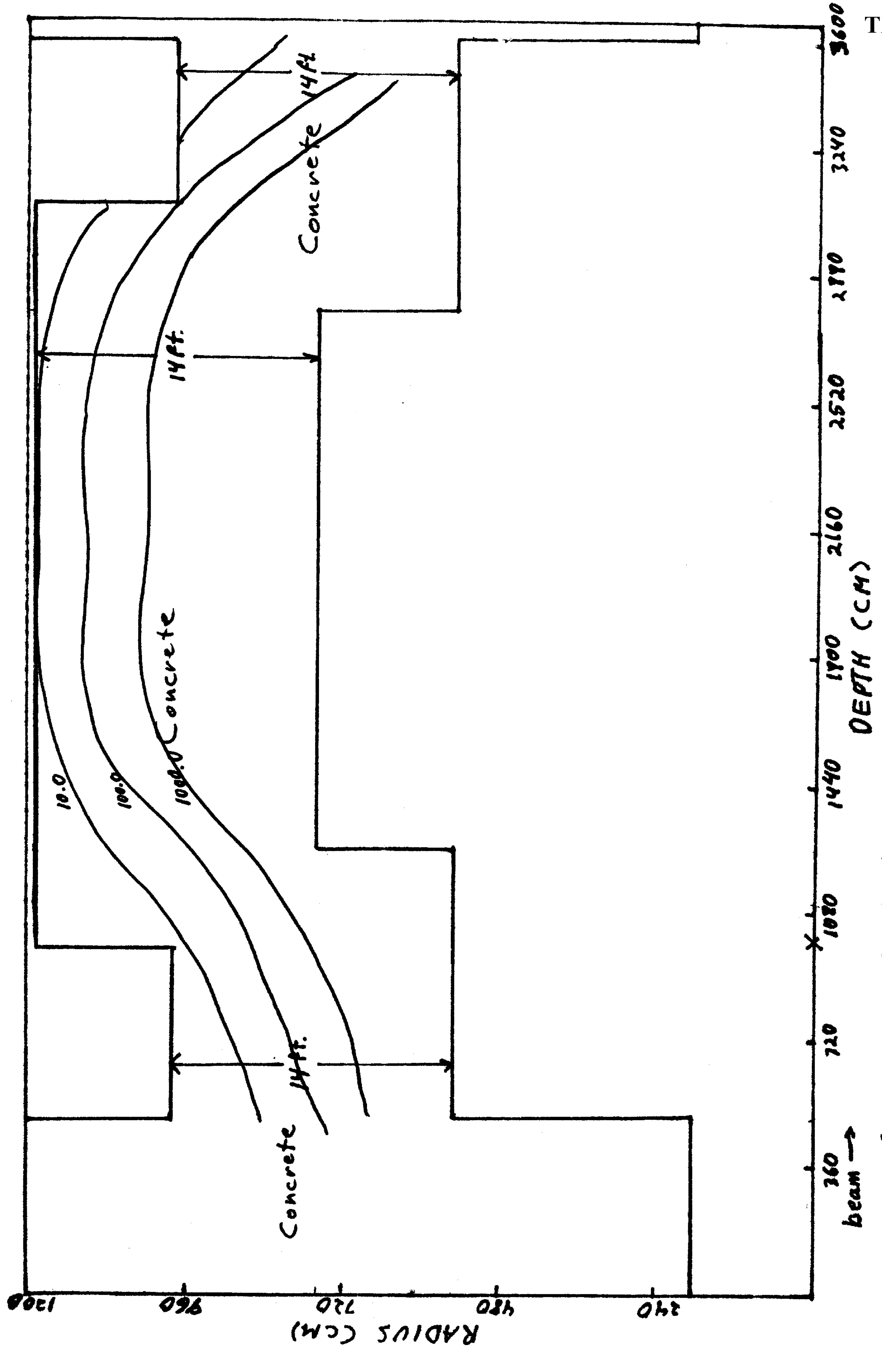


Figure 11 Case 3, Loss Point at Z = 1000.0 cm

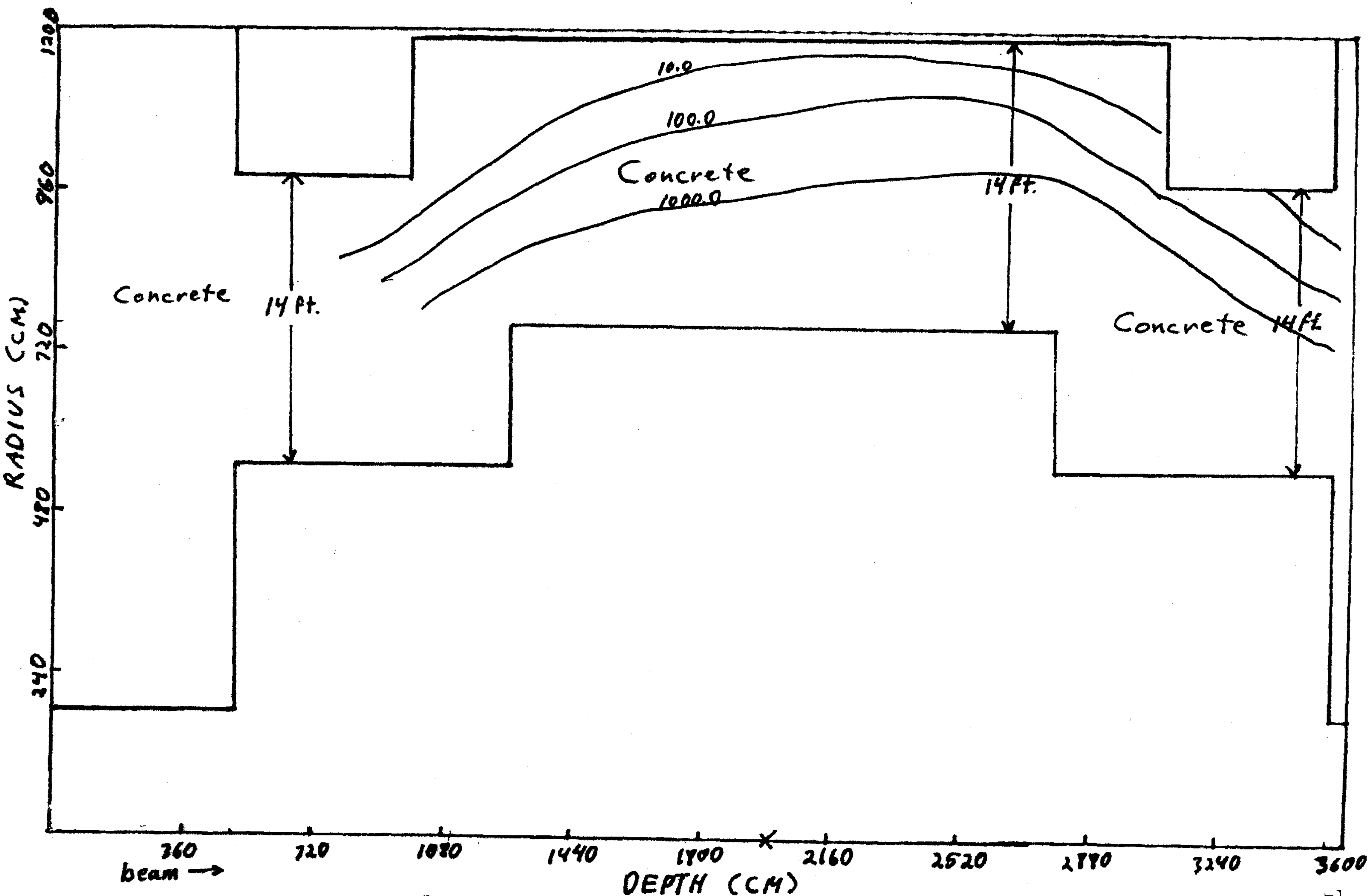


Figure 12 Case 3, Loss Point at z = 2000.0 cm.

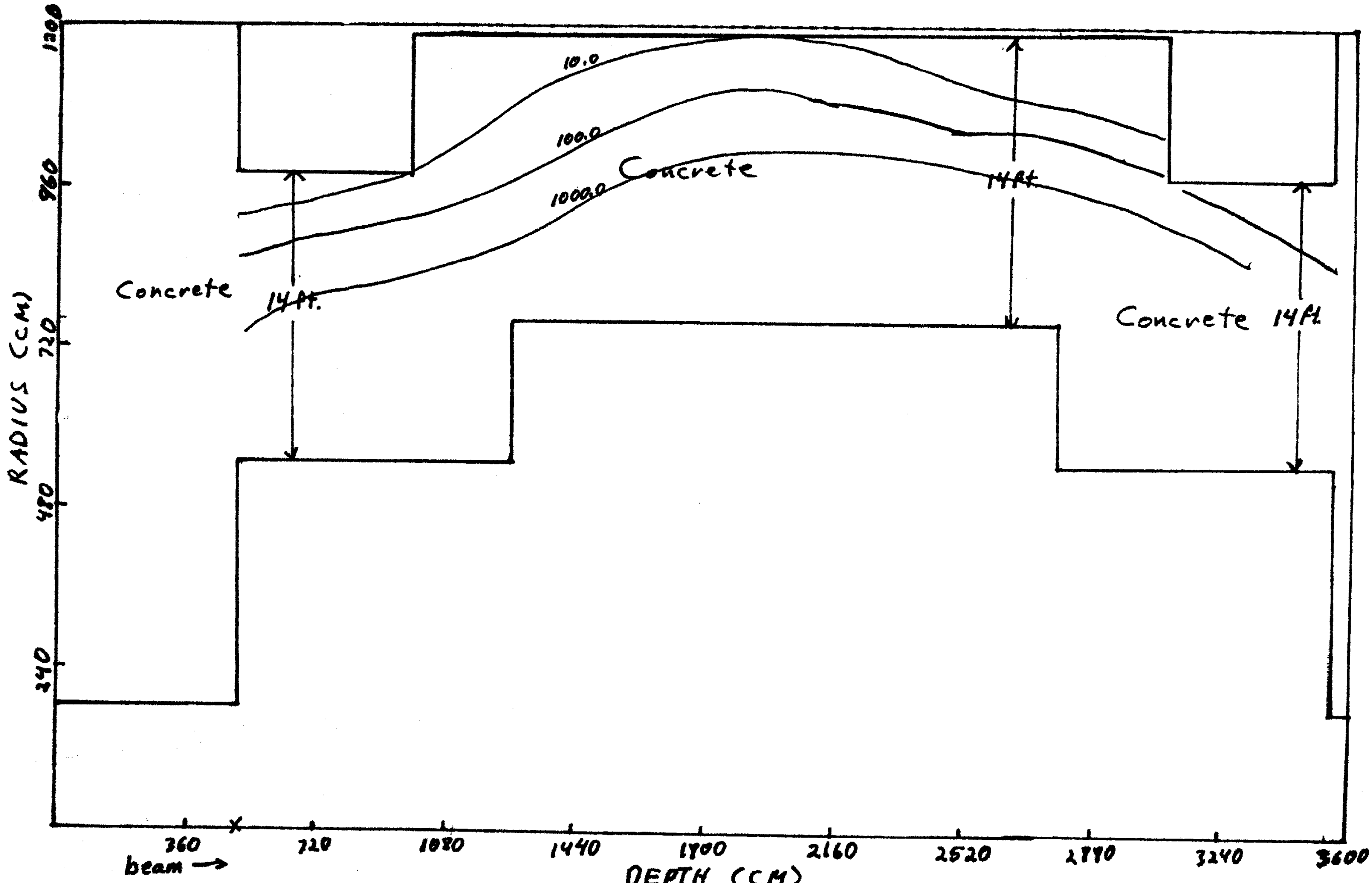


Figure 13 Case 4, Loss Point at Z = 500.0 cm.

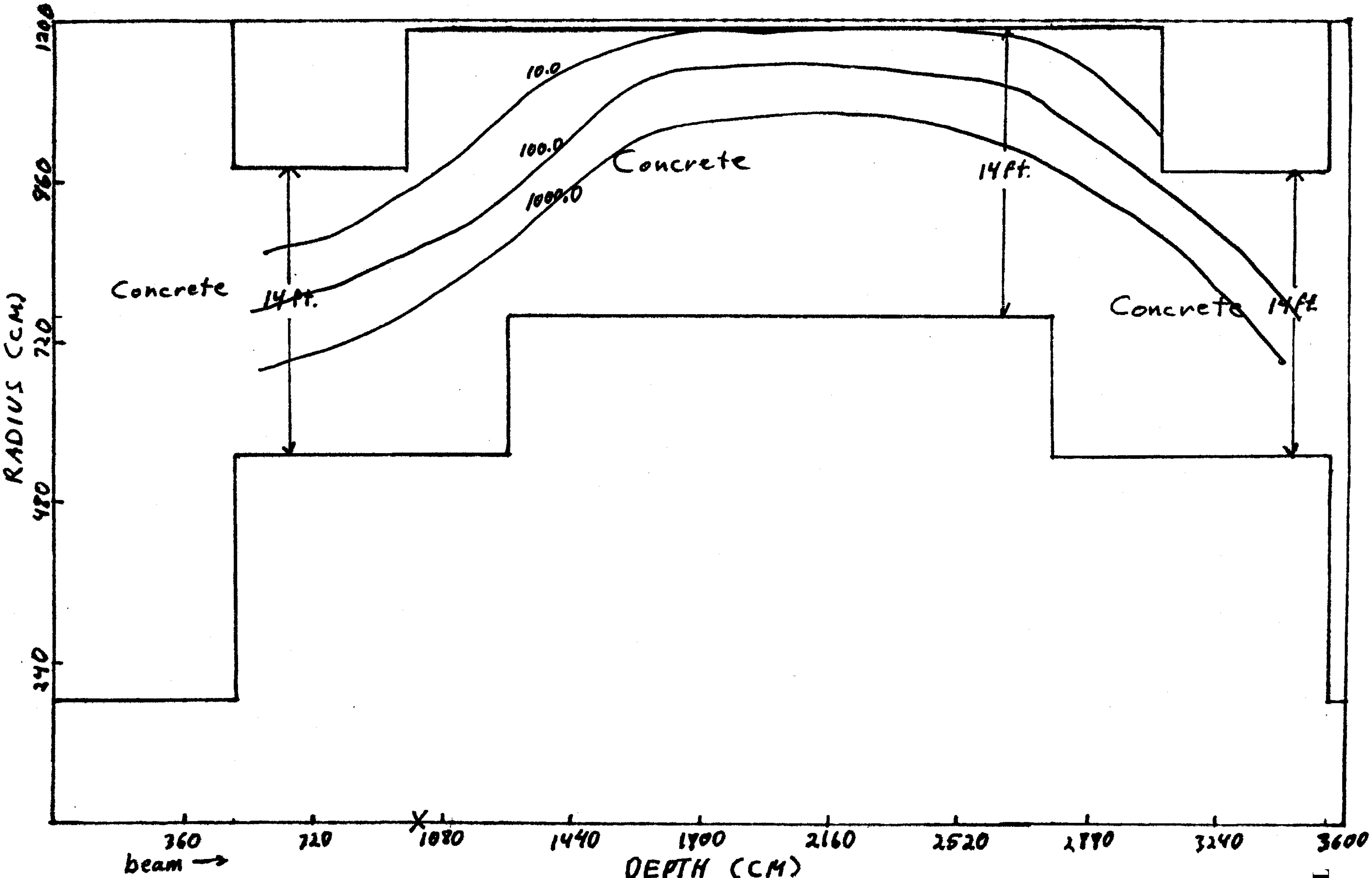


Figure 14 Case 4, Loss Point at Z = 1000.0 cm

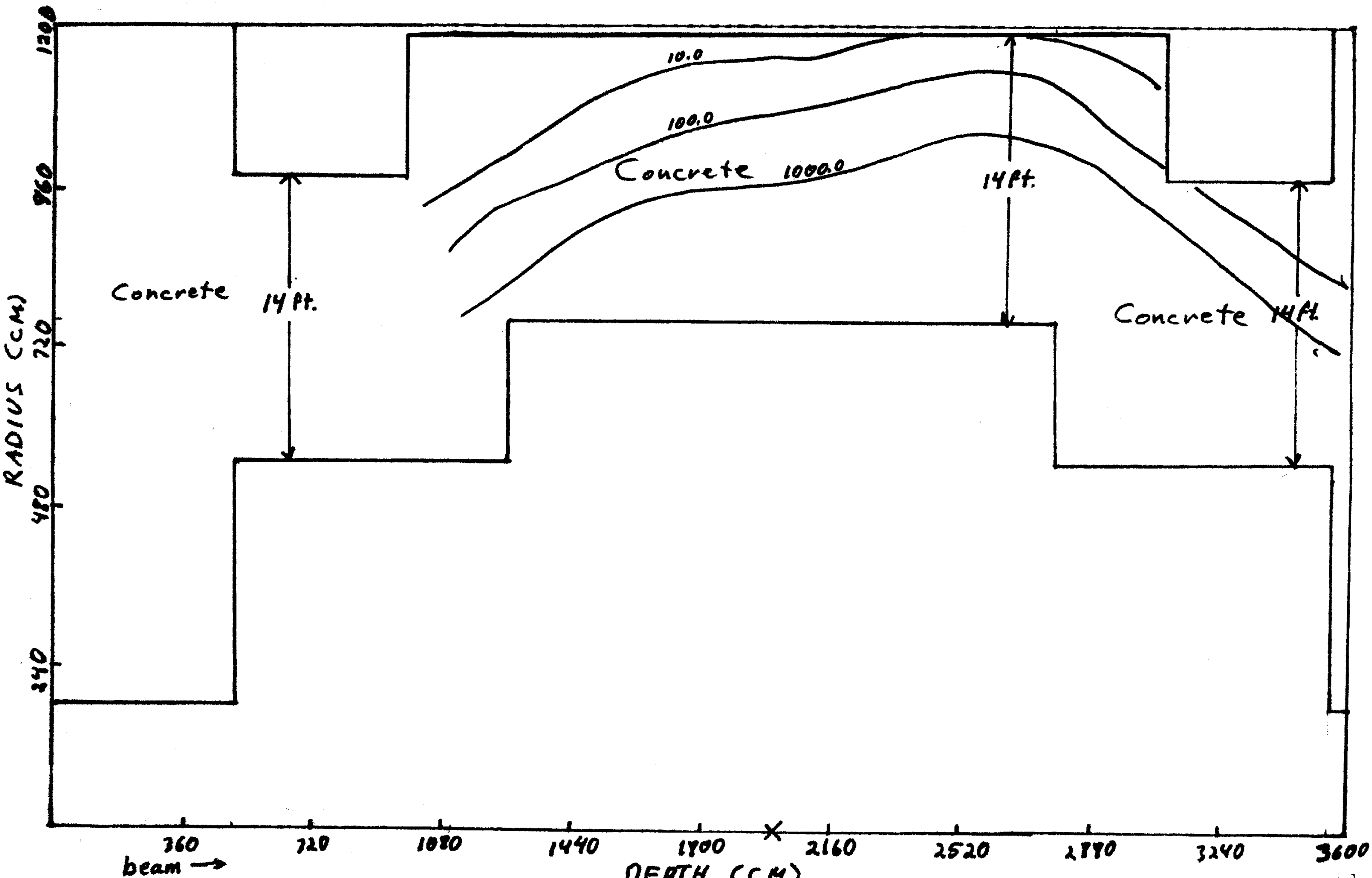


Figure 15 Case 4, Loss Point at z = 2000.0 cm.

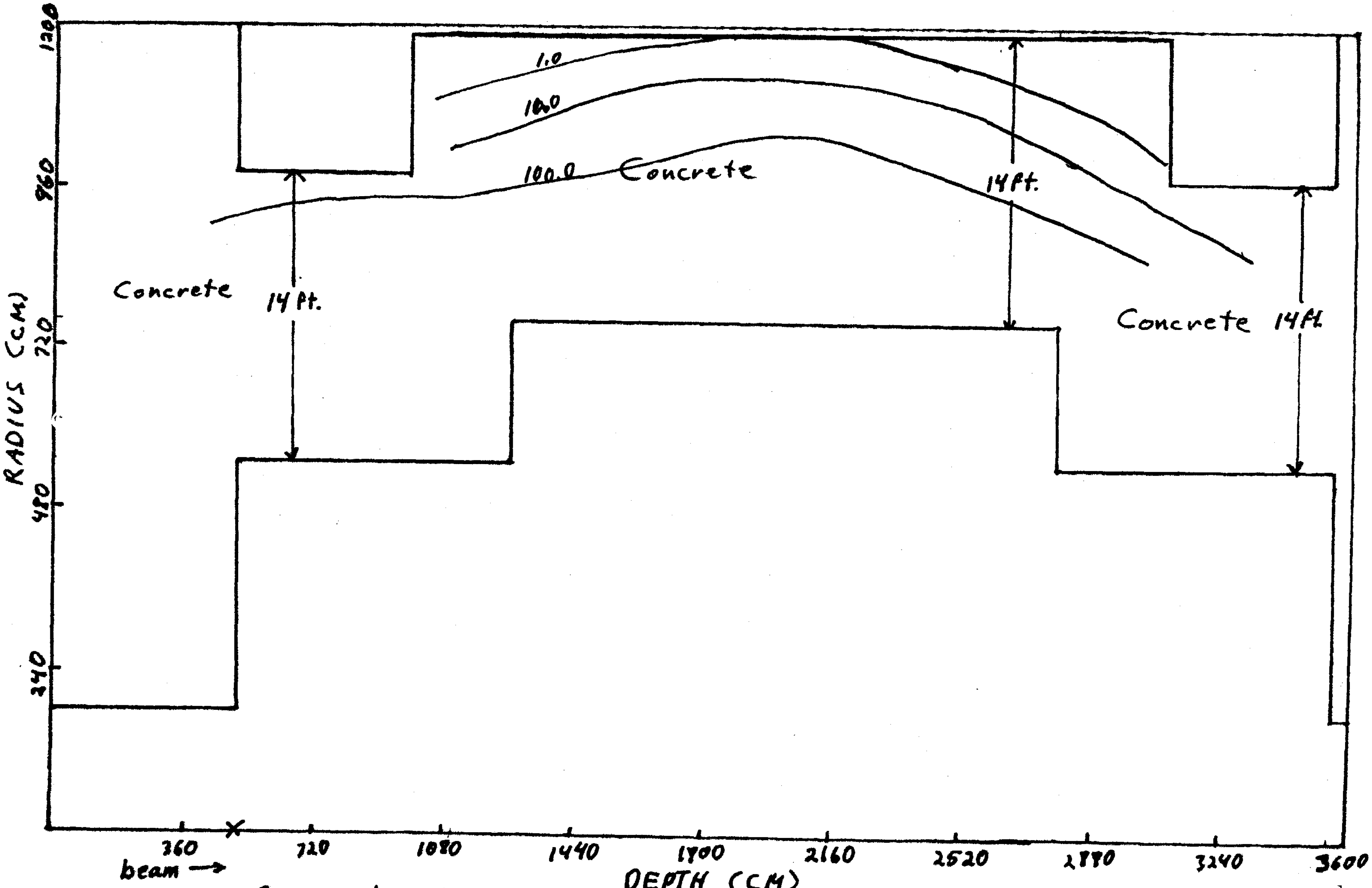


Figure 16 Cases, Loss Point at z=500 cm

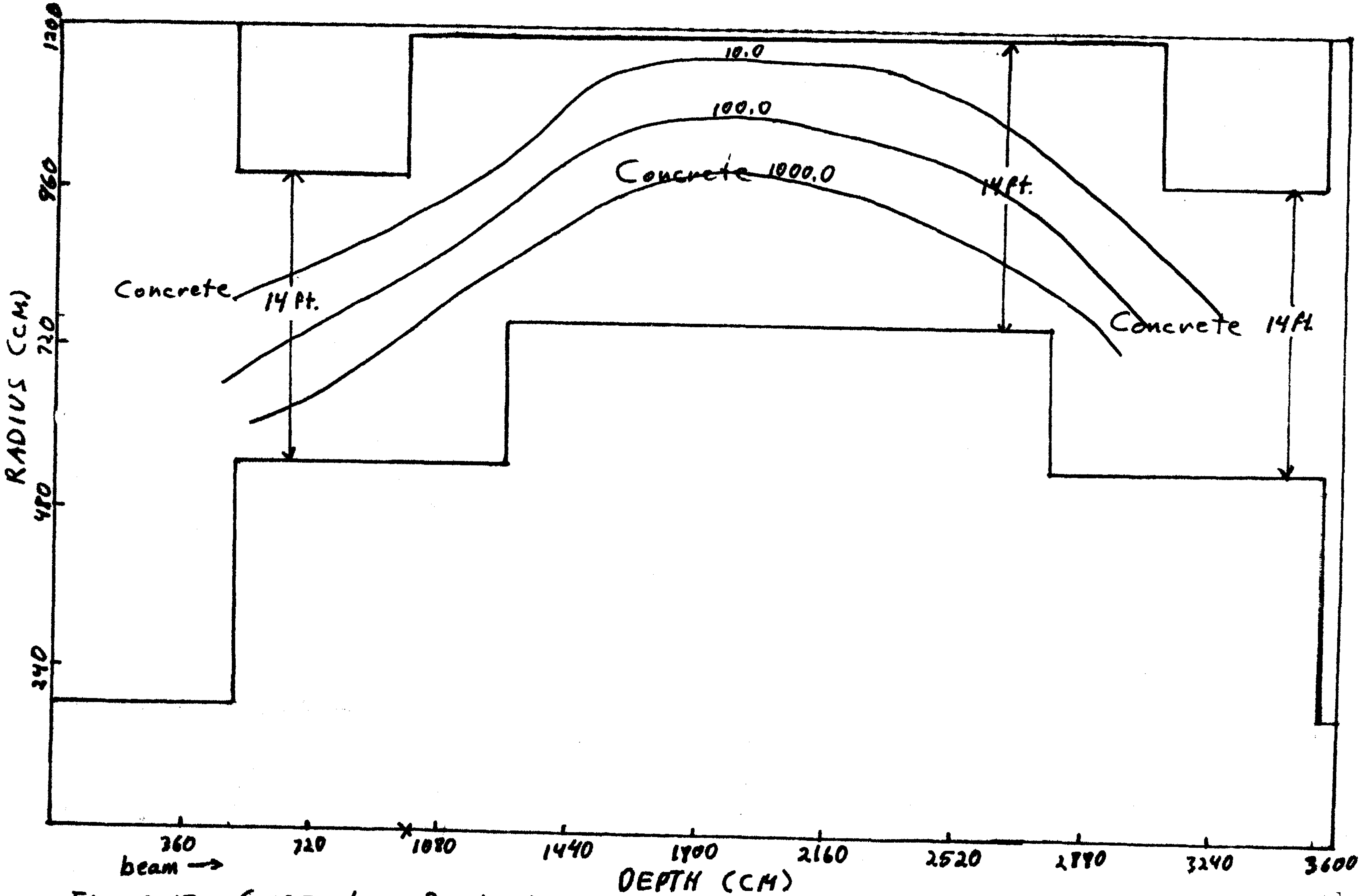


Figure 17 Case5, Loss Point at z=1000.0 cm.

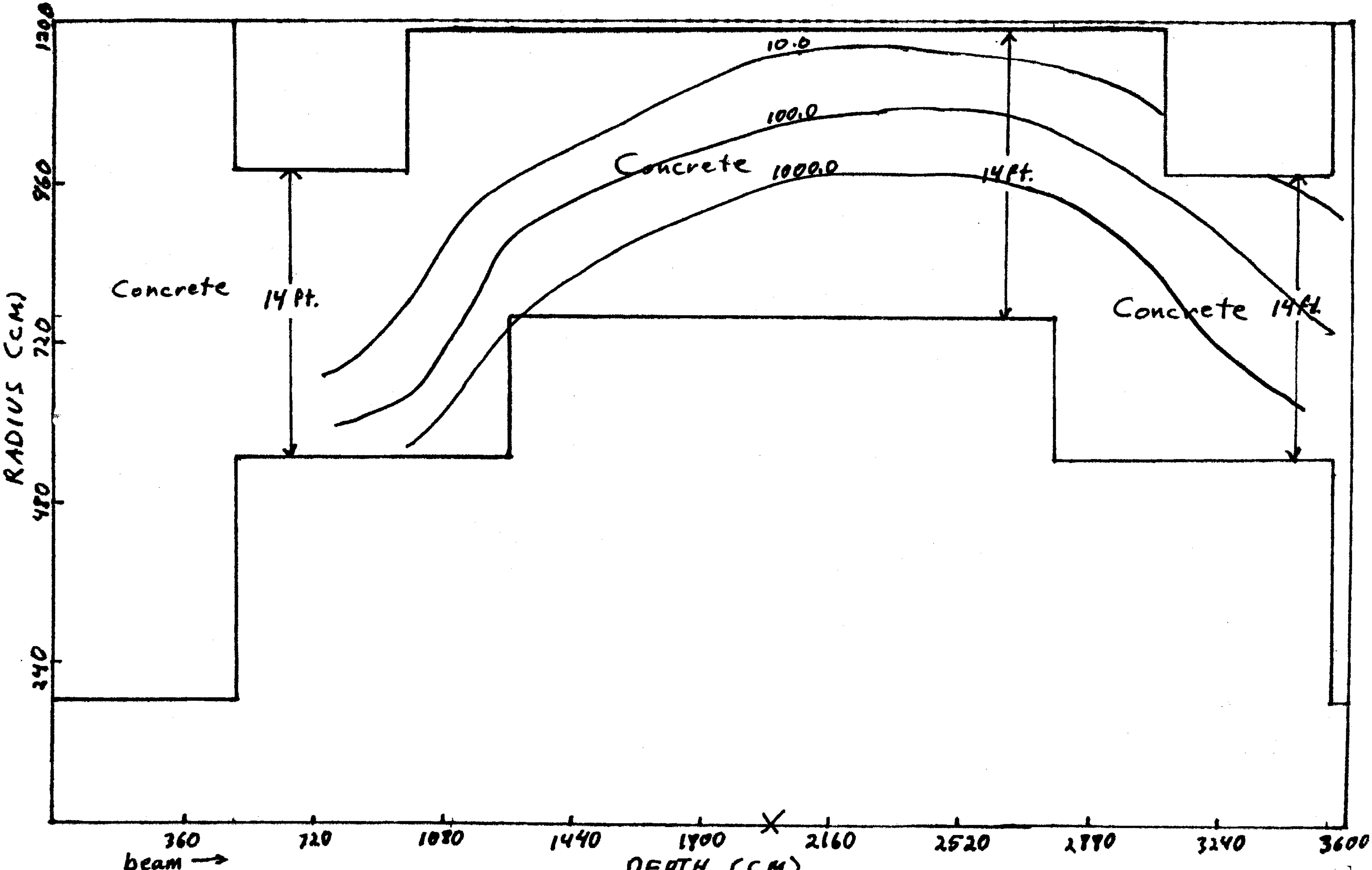


Figure 18 Case5, Loss Point at z=2000.0 cm.

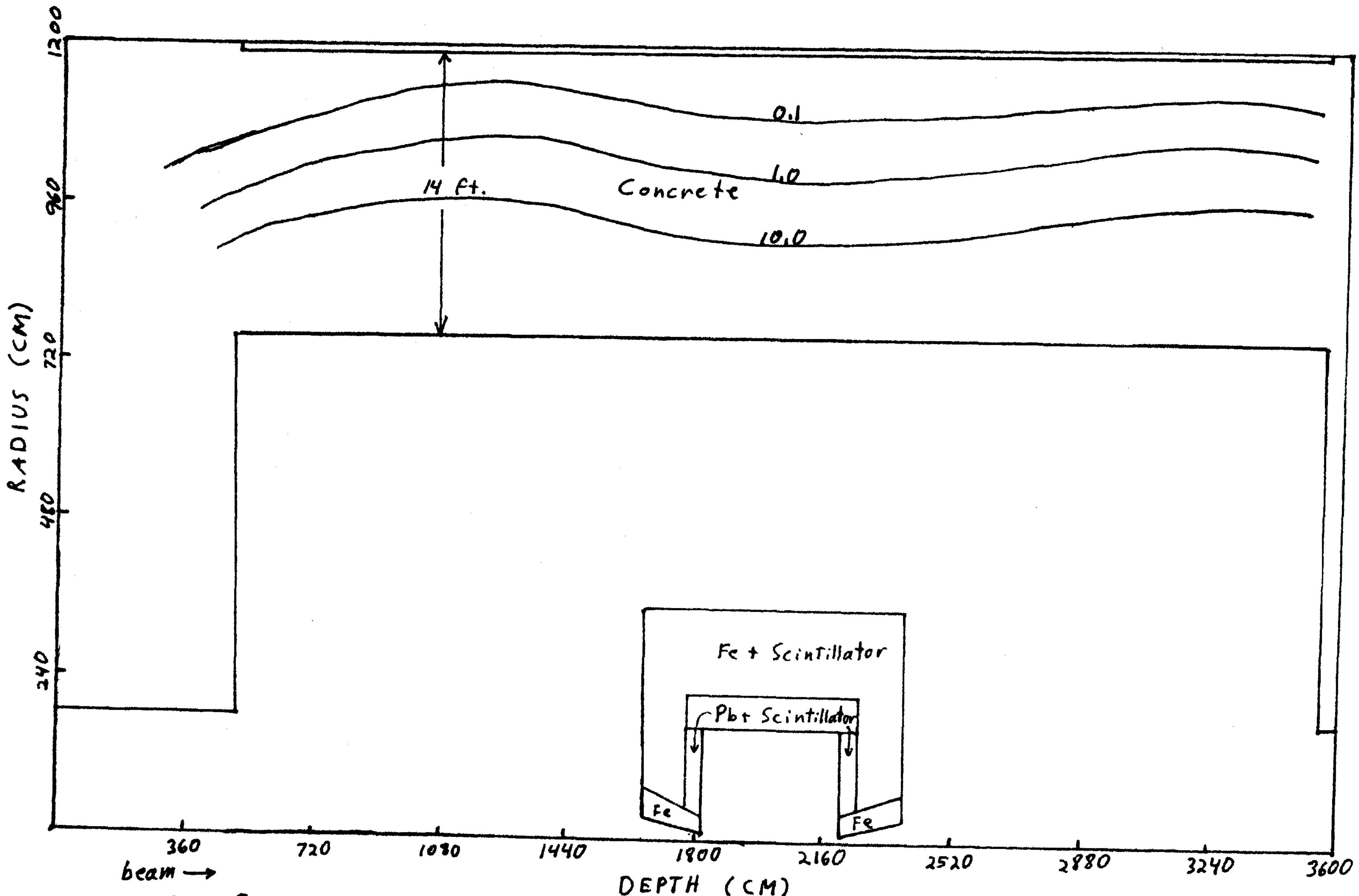


Figure 19 Case 6, Central Detector shown. The muon chambers are not included. Version shown is approximately that of H. Kautsky's drawing on Oct. 27, 1980

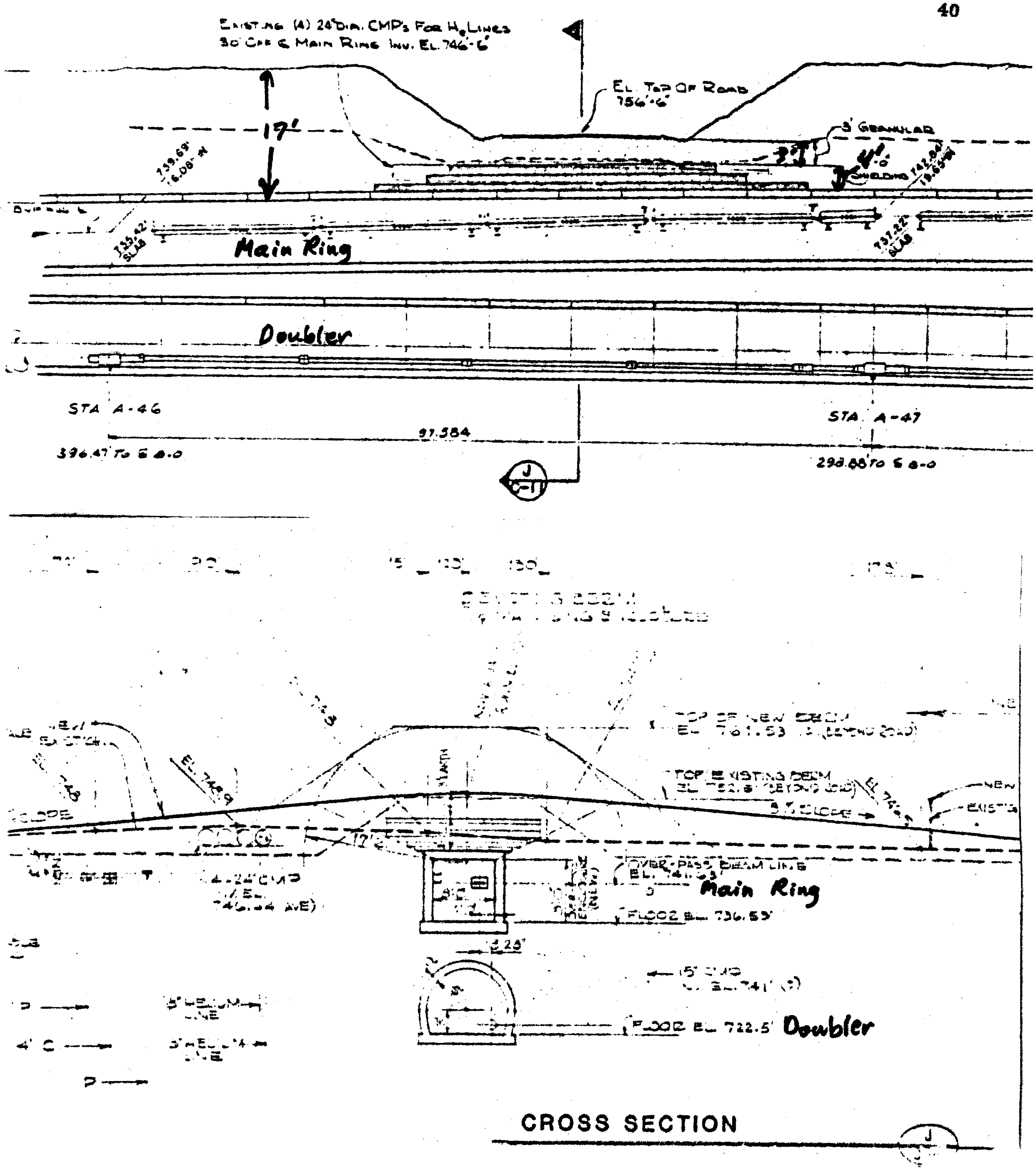


Fig 20 Cross Section and longitudinal Section of Road at A46

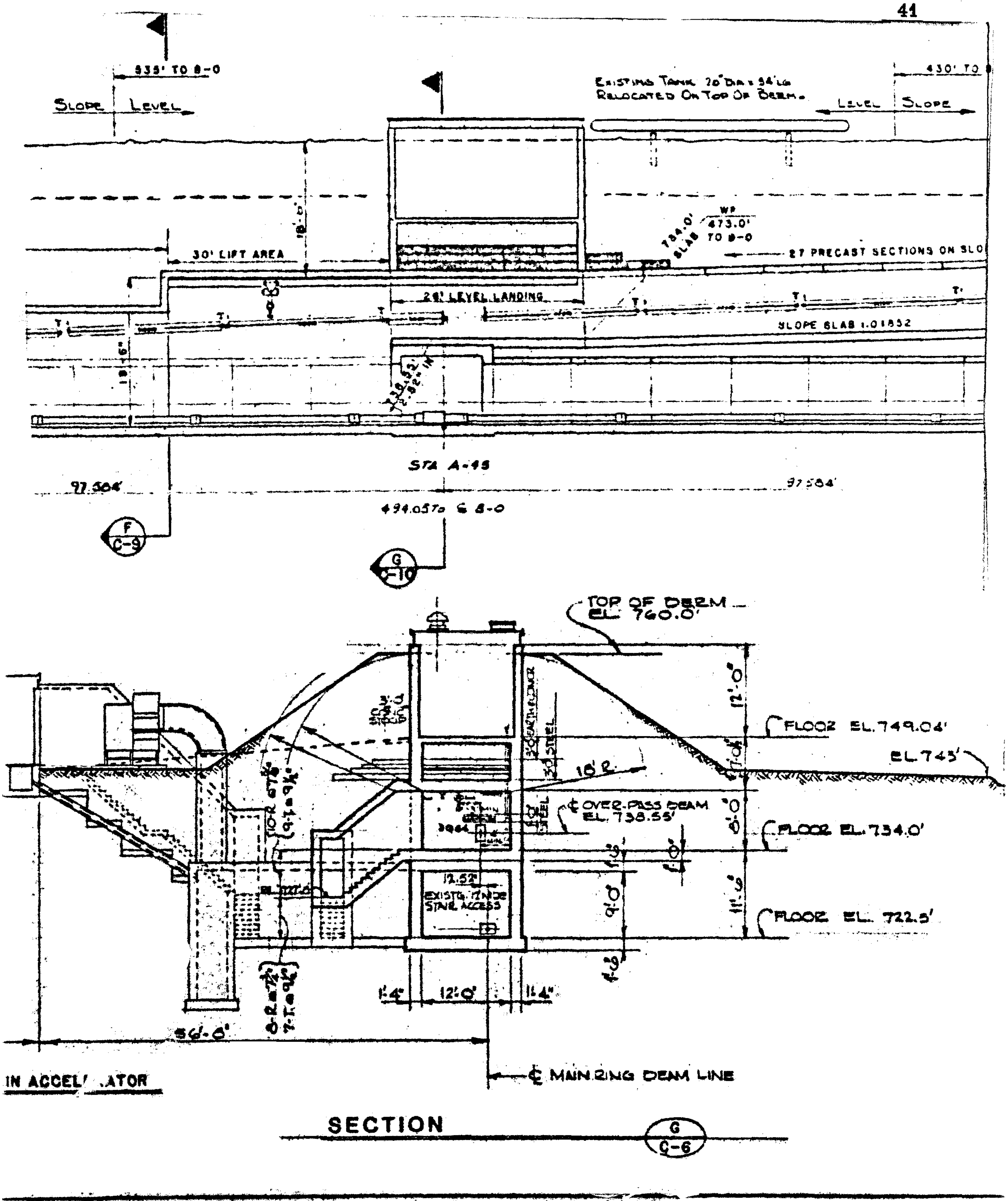


Fig 21 Sections of Road at A-45

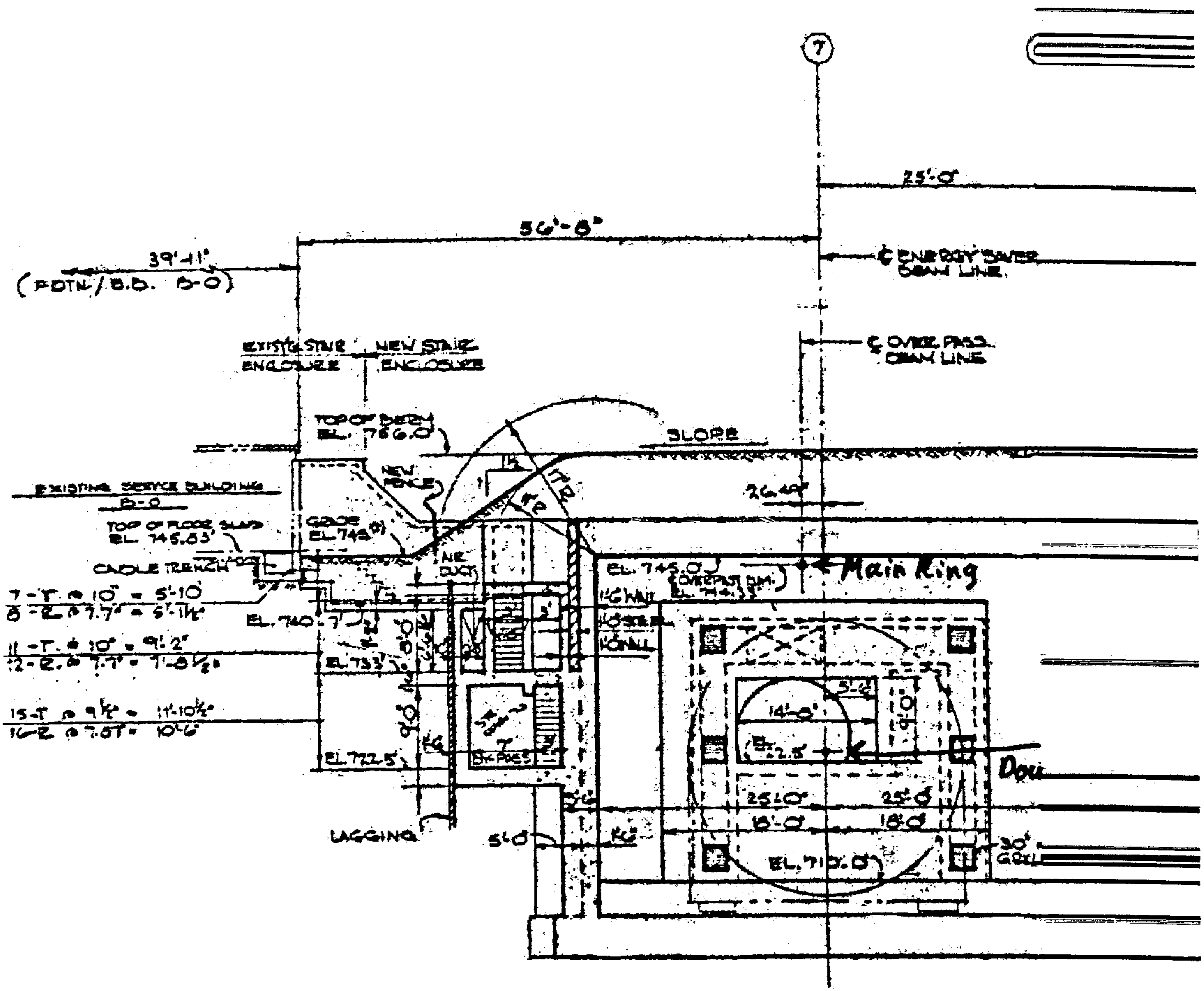


Fig.22 Cross Section at B-Ø showing Main Ring Overpass